ULTRASONIC BONDING OF IN/AU AND AL/AL FOR HERMETIC SEALING OF MEMS PACKAGING

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ABSTRACT

In this paper the feasibility of ultrasonic bonding for hermetic MEMS packaging has been demonstrated for the first time adopting two different sets of materials; indium-to-gold and aluminum-to-aluminum. The process utilizes purely mechanical vibration energy and enables low temperature bonding between similar or dissimilar materials without pre-cleaning of the bonding surfaces. As such, ultrasonic bonding can be broadly applied not only for electrical interconnection, but also for hermetic MEMS sealing and packaging especially where temperature limitation is a critical issue. This paper describes the ultrasonic bonding and hermetic sealing processes as well as the bonding tool characterization and equipment setups.

INTRODUCTION

Ultrasonic welding and joining have been used successfully in many applications such as wire bonding, plastic joining and flip chip assembly [1,2]. In addition to low temperature process, it has numbers of merits compared to other bonding methods. For example, it does not require pre-bonding preparation or post treatment, consumes very little energy and can be easily automated. Rapid bonding and low temperature processing are other attractive aspect. Ultrasonic bonding is also a. Even though the surface temperature may rise up to 200~300°C due to the friction of two contacting metal surfaces [3], the heating process is localized and bonding time is very short. For example, it has been demonstrated that ultrasonic bonding can be performed even under the liquid nitrogen environment [4]. It shows that the bonding process does not cause serious temperature increase of the bonded substrates and it can be one of the best choices for MEMS packaging where low temperature must be maintained. Also because the welding materials do not melt during the ultrasonic bonding process, the formation of harmful intermetallics is avoided.

Dissimilar metals such as ceramic and metal plates also can be joined together with this method [5]. Depending on the horn and die holder design, the ultrasonic bonding system is able to convert up to 90% of the input energy into welding energy. This paper describes the application of ultrasonic bonding to MEMS hermetic encapsulations for the first time.

ULTRASONIC BONDING PRINCIPLE

Ultrasonic bonding is a solid phase welding process in which the removal of contaminants from the two contacting surfaces of the weldments is very important. This is primarily accomplished by softening one or both of the weldments with ultrasonic energy or heat [6]. As explained in the mechanism of softening metals by Langenecker [7] , ultrasonic energy absorbed into metal causes multiplication and migration of dislocations resulting in an increase of density and mobility of dislocations and a reduction of shear stress necessary for plastic deformation of metals. Consequently, easy slip mechanism occurs within the crystal lattice of metal and yield strength is reduced. The resulting shear metal flow under compressive load pushes most of contaminants, such as oxides and dirt, aside into debris areas exposing essentially clean areas. Direct contact and diffusion at the newly generated metal surfaces result in bond formation. The heat generated by scrubbing two contacting surfaces during the bonding process is insufficient to melt most metals and therefore, melting temperatures and thermal conductivity of the weldments are not decisive process factors. However, the heat generated plays a significant role for the diffusion at the contacting surfaces and affects the bonding strength and quality. It is known that increasing ultrasonic power and bonding time generally enhances the diffusion process, for better intermetallic phase and stronger bonds [8].

EQUIPMENT DESIGN, SETUP, CHARACTERIZATION AND EXPERIMENT

The essential components for the bonding test are the ultrasonic transducer, power control unit and die holder. In this bonding test, an ultrasonic transducer and horn system for wire bonding and flip chip die bonding were used with a power control unit (Uthe Tech. Inc, 21PT and 50G). The power control unit maintains constant voltage for different types of die holders and generates ~60 kHz mechanical vibration through the transducer. When the friction load is applied to the die holder, the frequency is reduced slightly but the power control unit is designed to operate within a specified range of impedance such that the frictional load caused by the two contacting dies during the bonding process did not generate significant frequency shift. The ultrasonic frequency of ~60kHz used in this bonding test is generally applied for aluminum and gold wire bonding for electrical connection. Because the vibratory displacement at the end of a horn usually decreases as the frequency increases, transducers with lower frequencies than 60 kHz are typically used in macro scale ultrasonic welding applications and higher frequencies are adopted for smaller feature bonding such as fine pitch wire and flip chip bonding. We concluded that about 60 to 75 kHz is a moderate frequency range for MEMS scale bonding and packaging applications, where the vibratory displacement is in the order of several μm.

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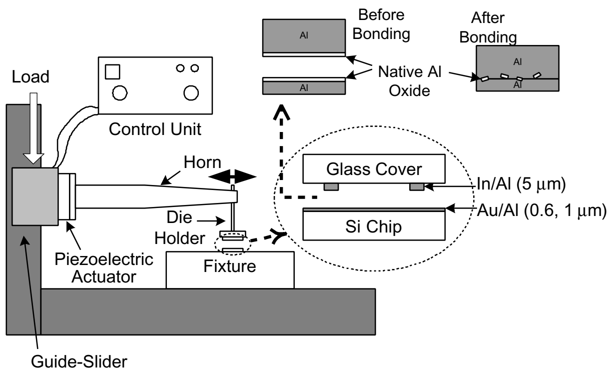


Figure 1. Schematic diagram of the lateral bonding equipment setup and the nature of Al-to-Al ultrasonic bonding

Figure 1 shows the equipment setup where the ultrasonic actuator is powered by a control unit and the vibration amplitude is measured by a laser interferometer. The transducer and horn unit is mounted on a slider which can move on a vertical guide so that the height of the horn can be adjusted for different specimen thickness and the required pressure on the die can be applied effectively. Load, vibration amplitude (or ultrasonic power) and actuating time are three important parameters in ultrasonic bonding. In this setup, load is applied vertically to generate pressure between two chips, and both time and power are controlled by the control unit. The actuator is composed of a piezoelectric transducer to generate high frequency vibration and a horn to amplify it. A die holder for mounting a topside glass cover is attached longitudinally at the end of the horn. The bottom silicon chip is attached to a fixture.

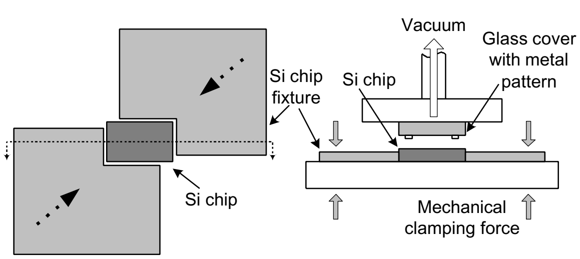
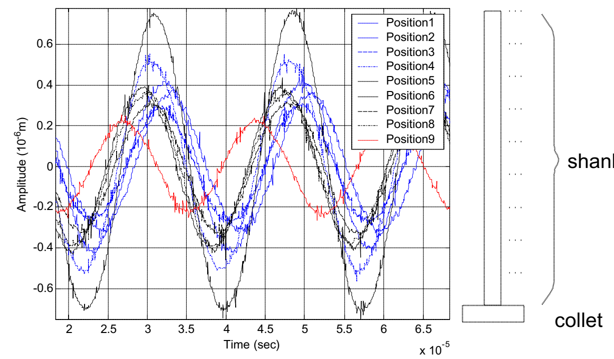


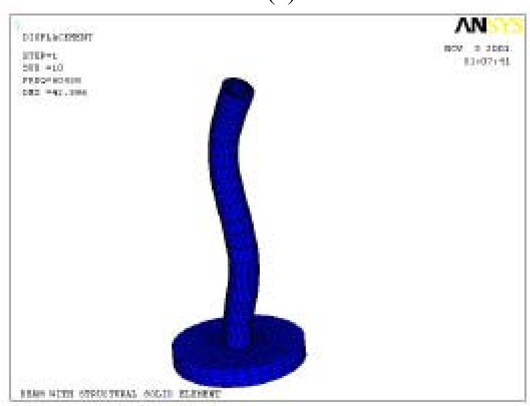
Figure 2. Die holding mechanism and fixture on the bonding equipment: (left) top view of the silicon die fixture, (right) side view of the whole mechanism

The rigidity of the die clamping device on the work stage is important to effectively generate the relative motion between the fixed bottom chip and moving glass cover. As shown in Figure 2, the glass cover is held on the die holder (tool) by vacuum force and the silicon chip is tightly clamped on the work stage by the holding fixture made of high stiffness tungsten carbide. This die fixture designed here gives very high rigidity in lateral direction, constrains the die at one fixed position and may hold different sizes of chips easily.

To find out the optimal die holder position for effective ultrasonic power transmission, the displacement of glass chip was measured using laser interferometer. We divided the whole length of the shank into 9 parts and conducted in-situ measurement of the collet displacement as shown in Fig. 3 (a) for each of the 9 positions through which the vibration energy is transferred to the die holder and therefore to the top side glass cover. Figure 3(a) shows that the pick-to-valley displacement ranges from +0.75μm to –0.75μm and the maximum power transmission occurred when the holder is attached to the horn at the 6th position. This measurement exactly matches with the finite element analysis result in Fig. 3(b). It clearly shows that the 6th position corresponds to the anti-nodal point where the vibration input should be applied to get large displacement at the collet. The frequency of this vibration mode is 60.4kHz which falls into the operating frequency range.



(a)



(b)

Figure 3. (a) In-situ measurement of the amplitude of vibration for loaded cases under various actuating positions along the die holder (b) FE modal analysis of die holder vibration

The vertical mode of ultrasonic energy transfer was also conducted. Figure 4 shows the setup of bonding equipment, which is a typical configuration for ultrasonic plastic joining applications. In this setup, the mechanical energy from the horn is directly transferred to the glass and silicon chips without passing through the die holder. So the ultrasonic energy is efficiently used for bonding and no characterization of die holder is necessary. However, when the bonded materials are brittle as in this experiment of silicon and glass bonding, they are easily broken on the rigid fixture under vertical vibration. For this reason, the rubber pad was inserted under the silicon chip. In addition to the protection of bonding chips, rubber pad gives two more functions; it holds the chips to maintain the alignment, and allows self-planarization of two contacting surfaces. This is important considering uniform contact of silicon and glass chips is one of the key conditions that should be satisfied for the successful hermetic sealing. Dummy silicon die was used to minimize the possible bending of test chips and to protect test chips from sticking to the rubber surface due to the increased temperature. Experimentally, the dummy silicon chip is bonded with the rubber pad and the In/Au bonding is successfully accomplished by this setup.

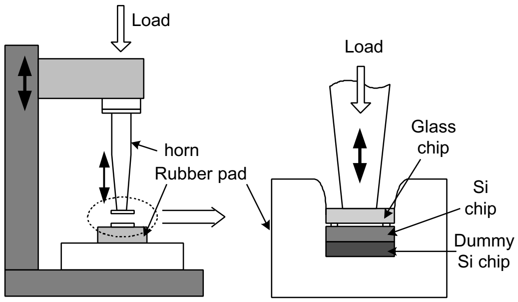


Figure 4. Equipment setup of vertical ultrasonic bonding

SAMPLE PREPARATION, EXPERIMENTAL RESULTS AND DISCUSSION

The test samples are prepared by two different sets. The first set is composed of 6000 Å gold-coated silicon chips and 5 µm-thick indium-patterned glass chips. The second set is 1µm –thick aluminum-coated silicon chips and 5µm-thick aluminum-patterned glass chips. All chips are cut into 4mm×6mm size for both glass and silicon substrates. A 3000 Å chromium layer was deposited first before aluminum for the second set. Cr layer between Si and Al is recommended not only because of the good adhesion characteristics of Si/Cr and Cr/Al, but also because Si is soluble in Al up to a few percent. Without the Cr layer, there may be the possibility of defects in Si under Al, which may cause the failure or reliability problem of hermeticity.

All bonding layers were deposited by metal evaporation. Deposited metals by evaporation or sputtering also form polycrystalline structures and native defects such as dislocation that may assist the bonding process [7]. Lots of grain boundaries and defects in evaporated or sputtered metals for electrical interconnection in IC devices cause problems such as high resistivity or electromigration but in ultrasonic bonding, those defects enable the decrease of yield strength of metals to be bonded and facilitate the plastic flow of metal under the propagation of ultrasonic energy.

Figure 5 shows the hermeticity testing result of gold-coated silicon and indium-patterned glass by immersing the bonded system into colored liquid. The liquid does not penetrate the bottom bonding-ring that has the outside diameter of 1200µm and width of 200µm and this shows that hermetic bonding is accomplished. For comparison, the top bonding-ring failed the gross leakage as shown. Figure 5(b) is presented to demonstrate the importance of ultrasonic bonding parameters. The square-shaped bonding ring here also hermetically seals the area inside, but the pattern spreads out significantly when the excessive ultrasonic energy is applied. As mentioned earlier, the temperature may rise up to more than 200°C at the contact interface during the bonding process and this is high enough to melt low melting point metal such as indium (156°C). This figure shows the negative effects of excessive ultrasonic bonding power or time such that relatively low power and short bonding time should be used to prevent the spreading of indium bonding patterns. On the other hand, small power may not form uniform and strong bond. With the vertical setup in Fig. 4, In/Au bonding was successfully demonstrated but the pattern spilled out more frequently. Therefore, when metal with low melting temperature such as indium is chosen as a bonding material for the applications where the fine feature of bonding pattern is required, optimal bonding conditions at which the metal does not melt but maintains strong bond as shown in Fig. 5(a) has to be established.

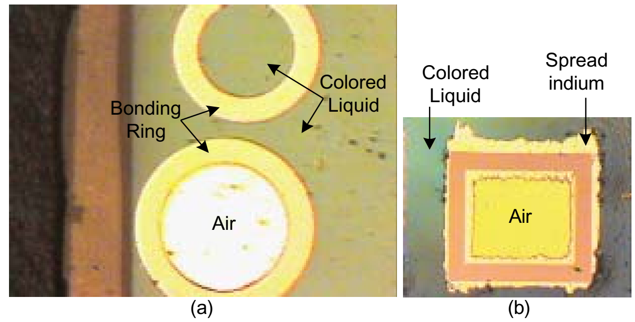


Figure 5. (a) Ultrasonic In/Au bonding under the leakage test showing hermetically sealed (below) and failed (top) bonding rings. (b) Ultrasonic In/Au bonding with spread pattern due to the excessive bonding power and time.

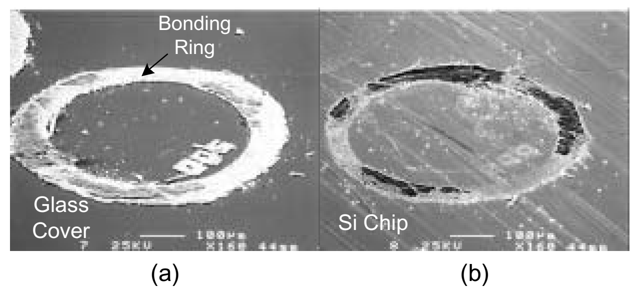


Figure 6. SEM microphotos of indium to gold bonding after the bond is forcefully broken : (a) glass cover and (b) silicon chip

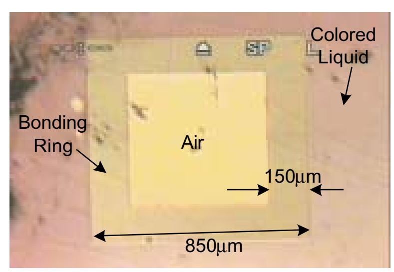


Figure 7. Hermetically sealed aluminum-to-aluminum bond by ultrasonic bonding

The bond is then forcefully broken and examined under SEM with the glass cover in Fig. 6(a) and silicon substrate in Fig. 6(b). It is observed that a great portion of gold layer that was originally on the silicon substrate has been torn off and is now attached to the glass cover. This shows the ultrasonic bond of indium-to-gold is comparable or stronger than the bond of gold-to-silicon. Similar phenomena are observed for aluminum-to-aluminum bonding shown in Figs. 7 and 8. No liquid leakage can be identified inside the square shape bonding-ring in Fig. 7 as hermetic seal is accomplished. The square bonding-ring is 850µm in size (outside width) and has a ring width of 150μm. Most of the aluminum pattern, which was originally deposited on the glass cover in Fig. 8(a) is now transferred to the silicon chip in Figure 8(b). In contrast to the indium/gold bonding, no spreading of patterns was observed in aluminum bonding regardless of the amount of applied ultrasonic power or time.

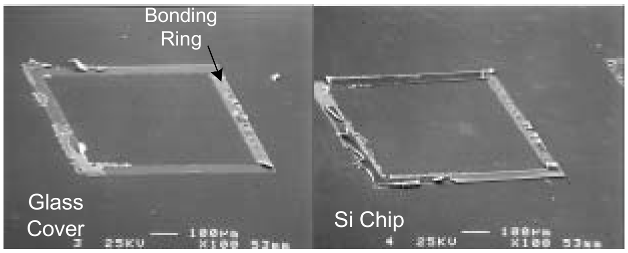


Figure 8. SEM microphotos of aluminum-to-aluminum bonding after the bond is forcefully broken : (a) glass cover and (b) silicon chip

The pictures of bonding results shown above for In/Au and Al/Al are all performed with the lateral transducer and horn setup. If either the bonding power or time is reduced, it was observed that the bonding is formed only at the perimeter of the patterns and most of these dies failed in the hermeticity tests. From this fact, it is conjectured that the ultrasonic welding starts around the perimeter first, and propagates to the inner area of the pattern. As the bonding power and time are increased, the number of dies that were successfully bonded and passed hermeticity tests also increase although the variation was large even under the same bonding conditions. Different bonding periods ranging from 0.1 sec to 10 sec were applied for the same pattern shape and area. When the bonding time is smaller than 5 sec for the aluminum case, the number of successfully bonded patterns (there were 6 patterns on one die) increased proportionally with time. No obvious correlation can be drawn between the bonding interfacial features and bonding time when the ultrasonic actuator was activated for more than 5 seconds. This saturation point of bonding time is expected to increase when the area to be bonded is larger. For the indium to gold bonding, the overall bonding time required was shorter (mostly less than 1.8 sec.) than aluminum bonding, but again the variation was quite large.

Table 1. Bonding parameters used in the experiments

Parameters	In/Au	Al/Al
Power supply output	20~25 Watts	30~50 Watts
Bonding time	0.8~1.8 sec	2.5~5.0 sec
Pressure	9.2~15.4 MPa	20.8~40.1 MPa
Vibration amplitude	0.8~1.5 μm	0.8~1.5 μm
Total bonding area on one chip	1.59~2.12 mm^2	1.59~2.12 mm^2

All the parameters used in the experiments are appeared in table 1. The range of values for power, time and pressure shows upper and lower bounds with which at least more than one pattern out of 6 on the same die was sealed hermetically.

CONCLUSIONS

Ultrasonic bonding for hermetic sealing of MEMS packaging using several different metals as bonding layers has been demonstrated. Ultrasonic power, applied vertical load and operation time are three control parameters to achieve hermetic sealing for MEMS application. In addition to these variables (power, time, pressure), flatness of two bonding surfaces and intimate contact are also important parameters for successful bonding. To achieve hermetic sealing, precision setup of bonding system and fixture design is critical. Even though the ultrasonic bonding process generally does not require pre-cleaning of bonding interface or post-treatment, big particles or dusts must be avoided to achieve good contact of two bonding surfaces. Two different bonding equipment setups were used in this experiment and it was concluded that the lateral vibration setup gives better bonding results for MEMS packaging rather than vertical vibration setup. With proper wafer holder design, these ultrasonic bonding techniques may be extended to wafer level packaging while keeping the low temperature at the bonding interface and substrate.

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